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16. ABSTRACT

This report analyzes data relating to the atmospheric dispersion of SO_2 from the TVA Paradise Steam Plant in Western Kentucky, U.S.A. Extensive hourly air quality measurements for 1971 are compared with predicted values, obtained by using the well-known steady-state short-term Gaussian plume model for dispersion from an elevated point-source release. The comparison is in terms of annual average concentration values and the frequency distributions of the hourly values at five monitoring stations in the vicinity of the electric-power generating plant.

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Preface

The present study was initiated during the period August-September 1973, while Dr. Werner Klug (Professor of Meteorology, Technical University Darmstadt, Federal Republic of Germany) was a visiting scientist at the Meteorology Laboratory, National Environmental Research Center, Research Triangle Park, N. C. Dr. Klug had been invited to discuss air quality modeling activities in the U.S.A. and the F.R.G. in preparation for the 5th Meeting of the NATO Committee on the Challenges to Modern Society, Expert Panel on Air Pollution Modeling (held at the Danish AEC, Roskilde, Denmark in June 1974). Among many other activities during his visit, and largely on his own initiative, Dr. Klug commenced the present study following a visit to the TVA at Muscle Shoals, Alabama. A preliminary report on this work was presented at the NATO/CCMS meeting mentioned above. A more complete analysis is now available and, in view of the great current interest in the topic of dispersion from tall stacks, it is now published as a special report so as to make the results more widely available. It should in no way be regarded as a final analysis of the problem, but only as contributing to the informational base that is now rapidly growing as a result of several closely related similar studies that are near completion. It is hoped that it will make an important contribution to a more definitive evaluation of the current state-of-the-art as regards modeling the dispersion of gaseous pollution from tall stacks.

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Dispersion from Tall Stacks

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I. Introduction

Concentration fields downwind of large, single emission sources are nowadays very often calculated in connection with air pollution control measures. The values for the dispersion parameters that occur in the dispersion equation (in case of the Gaussian-plume model, the σ_z and σ_y values as a function of downwind distance) are usually those derived from previous diffusion experiments, where source heights were generally much lower than the effective heights for present-day large emission sources. Furthermore, in order to calculate a concentration field for a given meteorological situation, a scheme has to be used which relates easily accessible meteorological parameters (such as a low-level wind speed, incoming radiation, cloud cover, vertical temperature differences) to these σ-values. Such schemes have been devised in the past by several investigators, and the most well-known seems to be the Pasquill classification [1]. Pasquill, however, pointed out that his scheme, together with his set of σ-values, should only be used for ground or low-level sources and not for effective source heights of the order of several hundred meters, such as are common in the case of large power stations. Nevertheless these values are often used because so few others are available, and in the hope that the errors might cancel out in a statistical context. Thus calculations of concentration values averaged over a year or concentration frequency distributions for the year might be close to

reality. Another source of error is the calculation of effective source height, and here again reasonable results would only be expected on the average.

Looked at from another point of view, many previous investigators have devised different urban air pollution models where, in most cases, the large single sources were modelled in the above manner. Attempts have also been made to validate these models, which usually contain a mixture of large and small point sources as well as area sources (which may be either real or used for simulating numerous very small sources, e.g., as for domestic heating). Such validation attemps would give better insight into the problems connected with urban air pollution modelling if the verification for the classical problem of the large single-elevated source had been established in advance. This is especially true for many of the larger cities where large single sources, such as power plants or chemical factories, can make major contributions to the concentration field. Such contributions can be important over a wide range of distances, depending on the meteorological situation.

For these reasons it seemed worthwhile to try to validate (or at least to show the limits of) the model of the single-elevated point source (steady state short-term Gaussian-plume) when applied to a large source. However, as we see below, the data actually used in the present paper refer to a plant consisting of three stacks, i.e., of three elevated point sources. This means that we have to deal in most cases with the superposition of three plumes. It is obvious that certain conditions must be fulfilled by a data

set for it to be suitable for such a validation procedure. First of all, the data relating to the output of the source must be well-documented and on an hourly basis. Then the meteorological data for each hour should include wind direction, wind speed, and some information on atmospheric turbulence and/or vertical stability, in order to permit use of the Pasquill scheme or one similar to it. Hourly concentration measurements downwind of the source must also be available and there should be no background pollution. These are the minimum requirements for an acceptable data set.

II. Model Validation Procedure

After some discussion with colleagues from the EPA, and examining the availability of possible data sets, the data most suitable for the purpose appeared to be those from the TVA electric power generating plants, and especially those from the Paradise Steam Plant. This is located on the west bank of the Green River in Muhlenberg County, near the village of Paradise in Western Kentucky, USA. The plant has three units, of which units 1 and 2 have a capacity of 704 MW and unit 3 of 1150 MW. The stack heights are 183m, 183m, and 244m, respectively.

The facts which make this data set suitable are as follows. For the whole of 1971 the following data are available for this particular plant:

1. The daily SO_2 output data for each unit calculated from the daily coal consumption and a weekly average sulfur content of the coal. Since the coal used comes only from adjacent coal fields, the sulfur content is relatively constant.

2. The hourly total MW data for the three units together. This hourly value is used, as below, to estimate an hourly SO_2 output for each unit.

3. Hourly meteorological data. These consist of wind speed and wind direction at two different heights (13.4m and roughly 110m above the ground), vertical temperature differences between three different heights, surface temperature, surface pressure, amount of rainfall, total and solar radiation.

4. Hourly SO_2 concentration data for 6 sampling stations. Most of these stations are located downwind in the prevailing wind direction, and range in distance from approximately 3 to 17 km.

5. Empirical relationships for the dependence of stack gas exit velocity on MW load. The exit temperature of the gases does not vary significantly with load and was therefore assumed to be constant.

Furthermore, there seems to be no background concentration (SO_2 or other substances to which the conductivity method of concentration measurement might be sensitive) in the area and the surroundings of the site are relatively level compared with the effective heights of the plumes.

The procedures for calculating the surface concentrations [the concentrations due to the three individual units are calculated and then summed] at a receptor point are the following:

1. Determine the source output data for each unit.

   a. The hourly SO_2 output is determined for each unit by multiplying the daily SO_2 output by the ratio of total hourly MW load to the daily average total MW load.
   Result: Hourly SO_2 source strength in g sec^{-1}.

   b. The hourly exit velocity for each unit is determined by multiplying the total hourly MW load by a regression factor (supplied by TVA), multiplied by the ratio of the daily unit source strength to the sum of the three unit source strengths.
   Result: Exit velocity in m sec^{-1}.

   c. Use the constant exit temperature of each unit (413.2° for units 1 and 2, and 402.2°K for unit 3).
   Result: Exit temperature in °K.

   d. Compute the effective source height for each unit by using Briggs formulation [2] using the unstable, neutral or stable equations depending upon the stability. The stability is determined from the measured temperature differences between 1m and 110m above ground. The wind speed used is measured at 110m.
   Result: Effective source height in m.

2. Calculate the hourly concentrations using the hourly meteorological data:

a. If the wind direction at 110m averaged over one hour is outside a sector, which is defined by the bearing from true North of the receptor station with respect to the source, increased by (180° ± 45°), then the concentration at this receptor point is set equal to 10^{-30} g m^{-3}. (i.e., is negligible.

b. If the wind direction is within this sector, the concentration is calculated by using the standard bivariate Gaussian distribution for the concentration where -

(1) The wind direction at 110m and the bearing and distance of the receptor are used to calculate the x and y coordinates of the receptor.

(2) The temperature difference between 110m and 1.5m and the wind speed at 13m are used for determining the stability class by the following scheme:

U_{13m} m sec^{-1} \ $\Delta T_{1m-110m}$ °C	> 4.	4.0-3.0	3.0 -0.5	0.5- -1.5	< -1.5
≤ 5	A	B	C	D	E
> 5	B	C	C	C	D

This scheme for stability classes was set up after a number of test calculations, by relating the C-class to near adiabatic stratification, and the extreme values of observed differences to classes A and E, respectively.

(3) The standard deviations in the vertical and horizontal direction σ_y and σ_z are used according to the above scheme and

(a) Pasquill's original σ-dependencies on distance and stability classes [See Workbook of Atmospheric Dispersion Estimates, by D. B. Turner, U.S. Environmental Protection Agency, 1970].

(b) Pasquill's new power law dependencies for σ_z obtained from F.B. Smith's K-theory computations, and given in the latest edition of his book (Pasquill 1974). The σ_y values were same as for (a).

(4) The wind speed at 110m.

c. After the total hourly concentration due to the three stacks is computed for this measured wind direction, this wind direction is then arbitrarily changed by amounts $\pm 10°$, $\pm 20°$, $\pm 30°$ and the total concentrations are computed again. This is done in order to study the influence of changing wind direction with height.

d. The concentration which is closest to observed concentration is noted.

e. These 8 concentrations (7 computed ones and 1 observed) are stored on tape.

f. For all 8 data sets the frequency distributions are calculated and compared. Since the "measured wind direction" set gave the best agreement with observation these comparisons are not discussed any further.

g. The annual mean value, the standard error of estimate and the correlation coefficient between the logarithm of concentrations are calculated. [The correlation coefficient is a measure for the linear (stochastic) relationship between two normally distributed variables. Since the distribution of concentrations (not counting negligible values) is approximately log-normal the correlation of the log-values appeared appropriate.]

Excluding those periods when either the meteorological or sampling equipment was not operating, roughly 300,000 concentrations were calculated and compared with some 43,000 observed values, although many of these were zero.

III. Results

The screening of the observed concentration data showed that Station 6 (at a distance 12.7 km) showed no concentration values in the range 10^{-5} to 10^{-4} g m^{-3}, which is the decade just above the detection limit of 10^{-5} g m^{-3}. The data from this station were therefore not used.

1. Mean Values

The mean values for the whole one-year period were as follows [the calculated values refer to the measured wind direction at 110m.]

Station (Number)	Distance (km)	Observed (10^{-5} g m^{-3})	Calculated (10^{-5} g m^{-3})	Ratio Calc./Obs.
I	2.9	1.0	0.8	0.82
III	4.6	0.7	1.3	1.83
IV	6.8	1.0	1.5	1.50
V	8.4	0.9	1.4	1.55
II	16.9	2.1	1.1	0.52

These results show an overcalculation at 3 stations and an undercalculation at 2. A number of different stability - diffusion category schemes were tried with the hope of improving the results. However, use of these different schemes only changed the level of over - or undercalculation and did not improve the agreement. [The class limits of the vertical temperature gradients were changed so that the number of cases per diffusion category was changed, which in turn changed the concentration statistics.]

Furthermore, the calculated values show a smooth variation with distance, with a maximum at about 7 km. On the other hand, the observed concentrations show an unexplainable irregular behavior with the highest concentration mean value at 17 km. The results obtained with the second σ_z-set mentioned above differed insignificantly from the first, and a separate discussion is therefore omitted.

2. Frequency Distributions

The frequency distribution of concentrations is plotted as cumulative frequencies on probability paper as a function of the negative logarithm of the concentration. (See Fig 1-5). The outstanding feature of all the distributions is the fact that there is a large fraction of the concentrations (in some cases more than 90%) that are below the threshold or detection limit of 10^{-5} g m^{-3}. This would be expected since the wind is only blowing a small fraction of the total period from the source site to a particular receptor location. The other interesting conclusion that may be drawn from the figures is that, for all six stations, the highest hourly concentrations occur more frequently for the computed concentration distribution than for the observed one, whereas lower concentrations closer to the threshold occur more frequently for the observed than the computed distribution. This gives rise to suspicion that the instruments measuring the SO_2 concentrations may record values of some concentrations

that are below the threshold of 10^{-5}g SO_2 m^{-3}, as though they were above this limit. If this turns out to be the case, the conclusions drawn from this study are, of course, invalid or partly valid.

3. Standard Error of Estimate and Correlation Coefficient. Whereas the quantities above did not consider observed and computed concentrations as synchronous data pairs, i.e., irrespective of when they occurred, the standard error of estimate and the correlation coefficient involve consideration of simultaneous values. The following results were obtained:

Station	Standard Error of Estimate 10^{-5} g m^{-3}	Correlation Coefficient
I	8.4	0.14
III	8.7	0.16
IV	9.4	0.16
V	9.2	0.12
II	8.5	0.15

4. Changes of Wind Direction

As was mentioned before, concentrations were also computed after changing the hourly measured wind directions arbitrarily by amounts of $\pm$ 10°, $\pm$ 20°, $\pm$ 30°. If, for each hour the concentration value is picked which gives best agreement with the observation, then the standard error of estimate reduces considerably, and the correlation coefficient is increased.

Station	Standard Error of Estimate 10^{-5} g m^{-3}	Correlation Coefficient
I	3.6	0.35
III	3.0	0.43
IV	3.3	0.44
V	2.8	0.43
II	5.9	0.47

These results indicate the sensitivity of the c[illegible]ncentrations to the wind direction (which is equivalent to the [illegible]tation of the coordinate system). It was anticipated that the (arbitrary) variation of wind direction might reveal a systematic deviation, in the sense that during daytime there might be better agreement if the wind direction was turned, say, 10 degrees to the right, as compared with perhaps 20 - 30 degrees to the right during the night. Although a systematic deviation of +20° (to the right), when applied to all the hourly wind direction values at 100 m. height, was found to give the best agreement for a subset of the observations, the improvement was insignificant for the whole data set.

IV. Conclusions

The conclusions which can be drawn from this study are the following:

1. The observed and computed mean values of SO_2 concentrations over a period of roughly one year, agree within a factor of 2.

2. The highest hourly concentrations occur more frequently for the computed concentration distribution than for the observed one, whereas lower concentrations that are closer to the threshold occur more frequently for the observed than the computed concentration distribution.

3. The standard error of the estimate between observed and calculated hourly concentration values is several times the annual mean value, and the correlation coefficient is low although significantly different from zero.

4. The standard error of the estimate between observed and calculated hourly concentration values can be reduced considerably and the correlation coefficient increased, if the measured hourly wind direction is changed arbitrarily by an appropriate amount for each hour.

5. There is some suggestion that the SO_2 instruments used in this study may record concentration values that are below the threshold value as being above it. This is suggested by the findings under (2) above. Another reason for suspecting instrumental deficiencies is the irregular behavior of the concentration mean values as a function of distance.

V. Acknowledgements

Part of the study was undertaken while the author was a visiting scientist with the Meteorology Division, NERC, EPA, at Research Triangle Park, N. C. The stimulating and helpful discussions with Messrs. K. L. Calder and D. B. Turner, and the programming assistance of Messrs. A. Busse and B. Dietzer are gratefully acknowledged.

This study would not have been possible without the help of TVA in providing and interpreting the raw data; special thanks are due to Dr. L. Montgomery of TVA.

VI. References

[1] Pasquill, F., 1961. The Estimation of the Dispersion of Windborne Material, Meteorolog. Mag., 90, p. 33-49.

[2] Briggs, G., 1972. Chimney Plumes in Neutral and Stable Surroundings, Atmosp. Environment, 6, p. 507-510.

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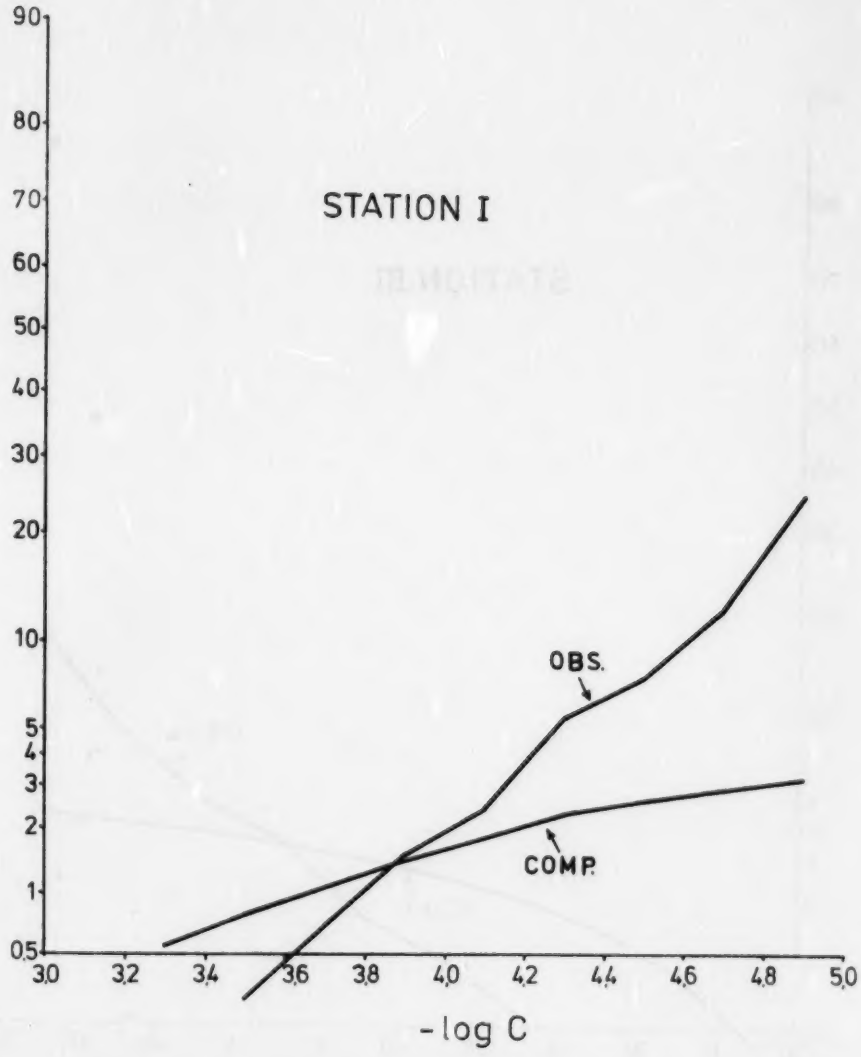

Figure 1. Cumulative frequency distribution of the negative logarithm of concentration (plotted on probability paper) for Station I.

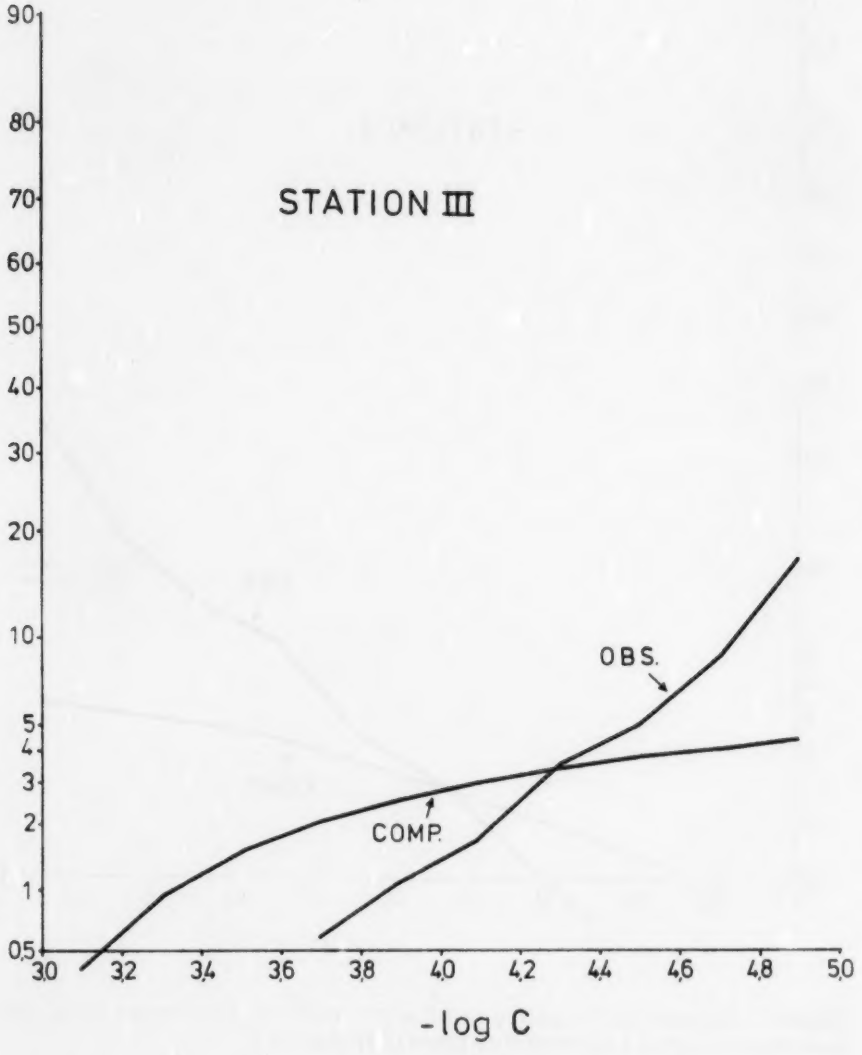

Figure 2. Cumulative frequency distribution of the negative logarithm of concentration (plotted on probability paper) for Station III.

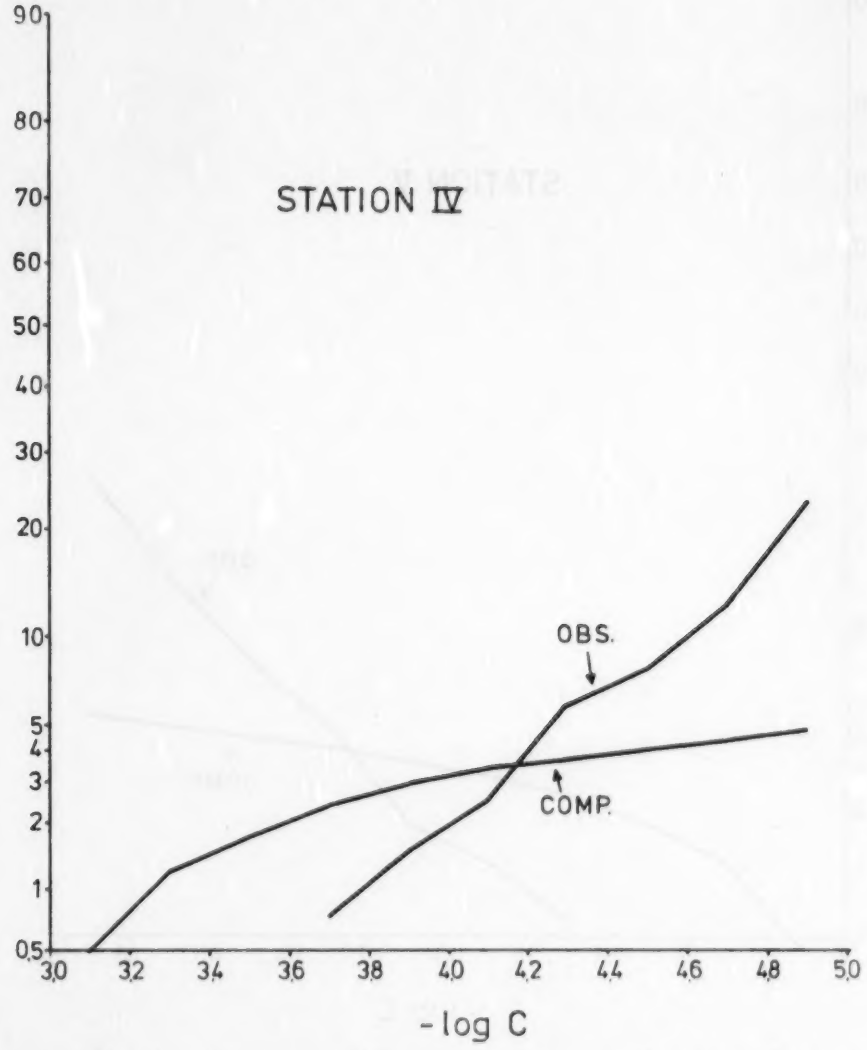

Figure 3. Cumulative frequency distribution of the negative logarithm of concentration (plotted on probability paper) for Station IV.

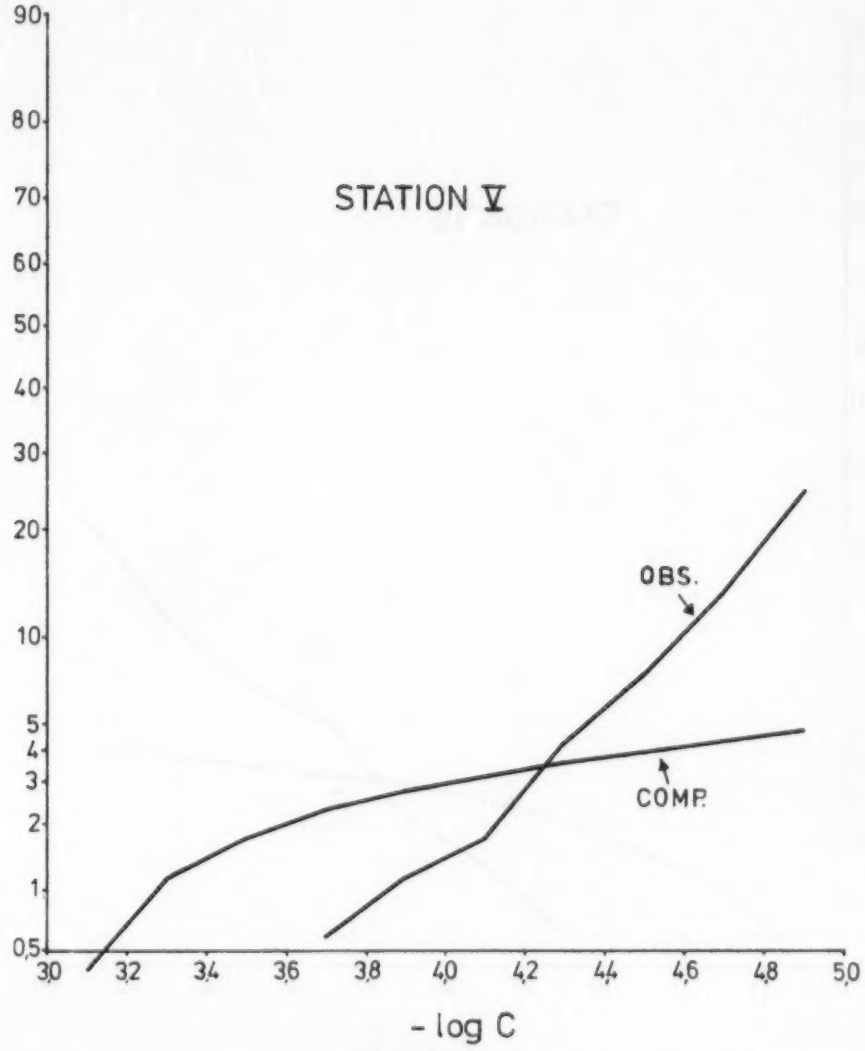

Figure 4. Cumulative frequency distribution of the negative logarithm of concentration (plotted on probability paper) for Station V.

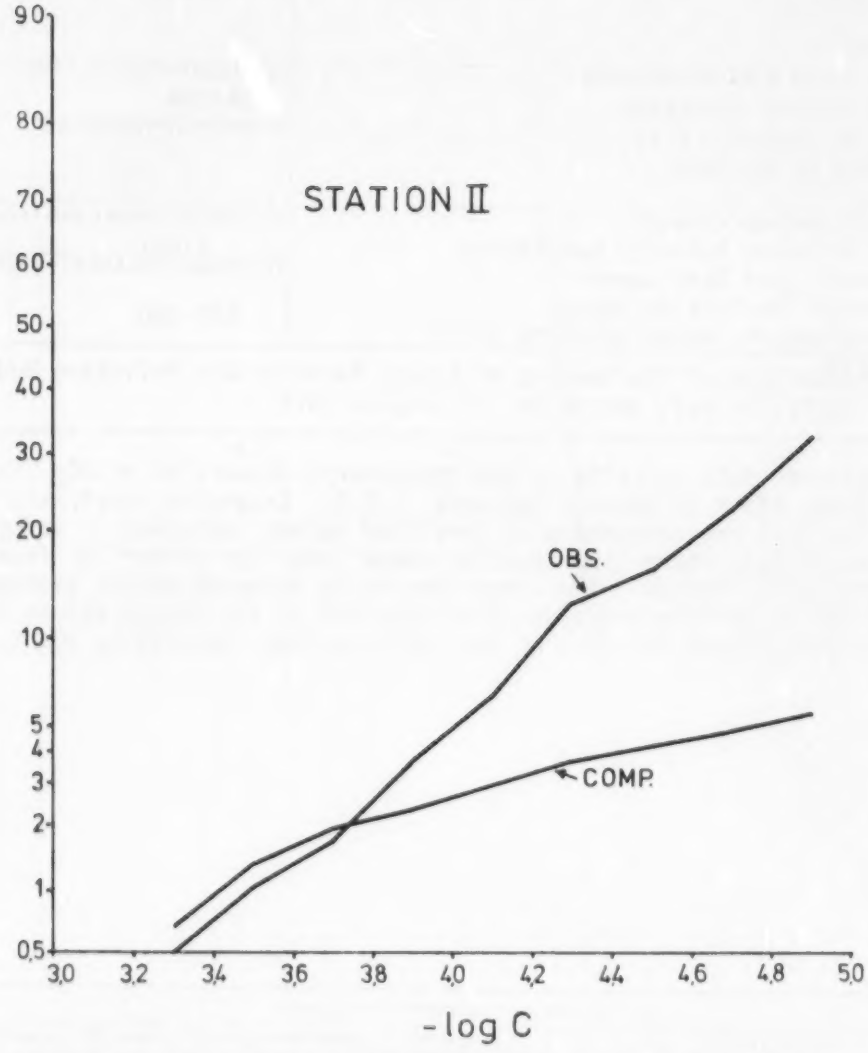

Figure 5. Cumulative frequency distribution of the negative logarithm of concentration (plotted on probability paper) for Station II.